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Production of large-area surface-wave plasmas with an internally mounted planar cylindrical launcher

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Abstract

We studied the characteristics of two different types of planar cylindrical microwave launchers installed inside the vacuum chamber for the production of a large-area processing plasma. The microwave launcher consisted of a coaxial waveguide and a cylindrical planar cavity, inside which a large-area thin quartz plate was inserted. We tested two configurations of microwave launchers; one was a closed cylindrical cavity structure and the other was a leaky open cavity structure. With a 1.5 kW microwave source, we demonstrated the production of large-area, surface-wave plasma (SWP) using Ar gas. Using the microwave launcher with a leaky open cavity structure, a spatial uniformity of SWP within $\pm 3.5\%$ over 160 mm in radius was achieved at a pressure of $20 \sim 30$ Pa. Numerical analyses using the electromagnetic wave simulator, MAFIA, were also carried out to study the electric field distribution radiated from the microwave launcher and to explain the experimental results.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

For recent large-size ULSI (ultra-large scale integration) or liquid crystal display panel manufacturing, it has been required to develop large-area plasma sources. In various plasma processes required in fabricating the electronic devices, such as etching, ashing or plasma chemical vapour deposition (CVD), spatial uniformity of the plasma source was one of the important issues, in addition to the demands of high density plasma or radicals. Furthermore, in the fabrication of amorphous or crystalline silicon films, diamond film synthesis and carbon nanotube growth, the large-area, high density plasma source has also been useful.

Among the various plasma devices, surface-wave plasma (SWP) is one of the promising plasma sources satisfying the requirements for a large-area plasma processing tool (Komachi and Kobayashi 1990, Sauve *et al* 1993, Werner *et al* 1994, Bluem *et al* 1995, Nagatsu *et al* 1996, Odrobina *et al* 1998). So far, we have been developing the large-area SWP excited by 2.45 GHz microwaves (Nagatsu *et al* 1997, 1998, Sugai *et al* 1998) or 915 MHz UHF waves (Nagatsu *et al* 1999) using a slot antenna technique. In the SWP, density jumps have been experimentally observed when the incident power or operating gas pressure changed (Ghanashev *et al* 1997). They originated from the surface-wave modes determined under the geometrical boundary conditions including the dielectric window and plasma at a given incident wave frequency (Ghanashev *et al* 1997). As the incident power or gas pressure was increased, the plasma density was selectively determined to satisfy the surface-wave modes. From a practical viewpoint, such a discontinuous behaviour of the plasma density is undesirable for material processing. Recently, it was reported that the mode jumps were suppressed by using a corrugated dielectric plate (Yamauchi *et al* 2001). Another issue in enlarging the plasma device is the mechanical and cost problem of the dielectric window needed for vacuum sealing, such as a quartz or alumina plate. When a metre-sized dielectric plate is used as vacuum window, it will take a huge mechanical force,

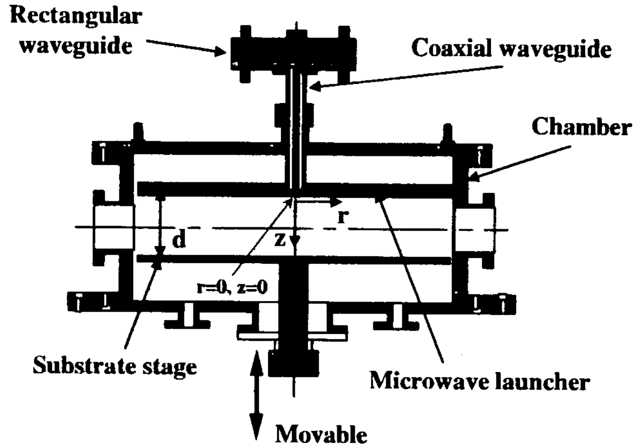

Figure 1. Schematic drawing of the experimental set-up with a planar microwave launcher.

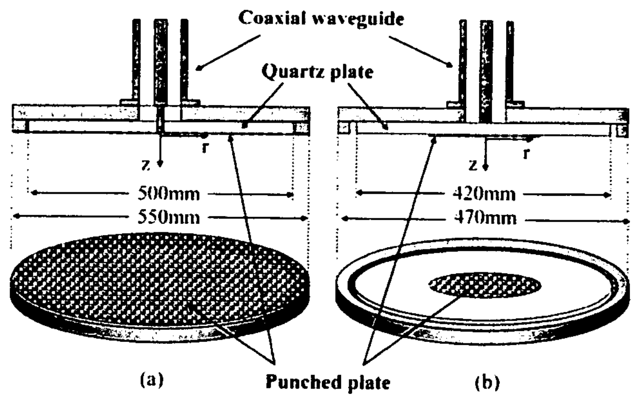

Figure 2. Structures of microwave launchers of (*a*) TYPE-I and (*b*) TYPE-II, where in TYPE-I, a punched plate having a hole size of 4–10 mm was attached to the front surface and in TYPE-II, a metal plate was partly attached in the centre of the quartz surface.

typically 10 tons per 1 m^2. To hold such a huge vacuum force, it will need a very expensive, thick dielectric plate.

In order to overcome these problems, we developed a new type of microwave plasma source with a microwave launcher installed inside the vacuum chamber (Nagatsu *et al* 2003, Ogino *et al* 2005). The microwave launcher consisted of a coaxial waveguide and a cylindrical planar cavity, inside which a large thin dielectric plate was inserted. A vacuum force is held in the small area of the coaxial waveguide in the proposed internally mounted launcher, so that we can realize use of a thin quartz plate. Moreover, we adopted a cavity type of microwave launcher to aim at suppressing the mode jump, which was observed in the slot antenna type of SWP. In the proposed microwave launcher, the electromagnetic wave modes are determined by the cavity geometry, without depending upon plasma density. It is expected that plasma density can change linearly with the incident microwave power without any significant density jumps. Experiments have been carried out to demonstrate the plasma production using a large-area stainless steel vacuum chamber with a diameter of 600 mm and a height of 350 mm. To understand the experimental results, we also performed a numerical analysis of electromagnetic wave fields using the field simulator, MAFIA (solution of Maxwell's equations by the finite integration algorithm).

In section 2, we describe the experimental set-up of a 600 mm-diameter microwave plasma source with the proposed microwave launcher. The experimental results of the microwave plasma production will be presented and discussed in section 3. Numerical analyses using the field simulator MAFIA are also given to study the microwave field distributions radiated from the microwave launcher. In the last section, we summarize the present study.

2. Experimental set-up

A schematic drawing of the experimental set-up with a microwave launcher is shown in figure 1 (Nagatsu *et al* 2003). The 2.45 GHz microwave guided by a rectangular waveguide was transferred to the microwave launcher via a coaxial waveguide. The inner conductor of the coaxial wave guide was water-cooled to avoid the thermal damage of an O-ring fitted on the edge of the inner conductor. Microwave power of 2.45 GHz magnetron was varied from 200 W to 1.5 kW. The reflected microwave power was minimized to almost zero by adjusting the 3-stubs tuners. Argon gas was introduced from the gas inlet located at the top of the vacuum chamber. The vacuum chamber was pumped down to an order of a millitorr by a rotary pump. For the measurements of plasma parameters, we used a Langmuir probe with a 0.6 mm-diameter platinum wire tip.

In figure 2, we show schematic drawings of microwave launchers. We tested two types of launchers, one a closed cavity type (TYPE-I) and the other a leaky open cavity type (TYPE-II). In the TYPE-I launcher, a circular quartz plate having a diameter of 500 mm and a thickness of 10 mm was used. A stainless steel punched plate with a hole-diameter from 4 to 10 mm was attached over the entire quartz surface, as shown in figure 2(*a*). With the TYPE-I launcher, plasma is produced in the narrow gap space between the metal punched plate and quartz plate or produced by the microwave leaked through a number of small holes as evanescent waves.

On the other hand, in the TYPE-II launcher, a 200 mm-diameter punched plate was attached in the centre of the quartz surface to block the microwave radiation directly from the central part, as shown in figure 2(*b*). It forms a leaky open cavity, where there is a narrow gap of 5 mm between the quartz plate and the metal ring frame. A quartz plate 420 mm in diameter and 15 mm in thickness was directly attached using a number of screws.

3. Experimental results and discussions

3.1. Production of microwave plasmas

We performed the plasma production experiments using two types of internally mounted microwave launchers, shown in figure 2. Figures 3(*a*) and (*b*) show pictures of Ar plasma discharges taken in the case of the TYPE-I launcher, where microwave power was 500 W and 1.5 kW at pressure of 10 Pa, respectively. These pictures were taken from the small side-port, so that they indicated only a half part of a large-area plasma discharge. As shown in figure 3, where the radial and axial axes are indicated, plasma spreads radially as the

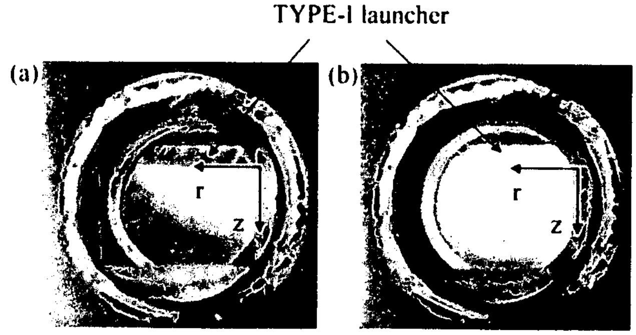

Figure 3. Pictures of Ar plasma discharges in the case of TYPE-I launcher where microwave power was (*a*) 500 W and (*b*) 1.5 kW at pressure of 10 Pa.

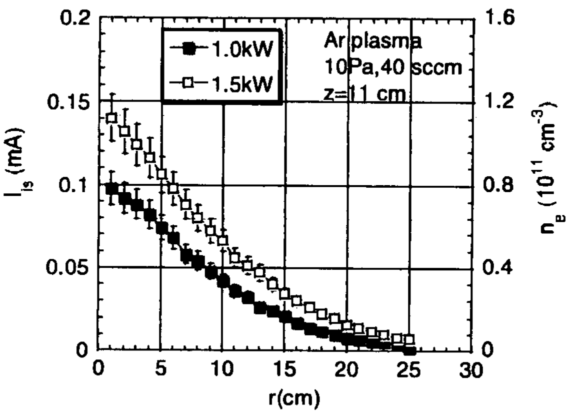

Figure 4. Spatial distributions of ion saturation currents at $z = 11$ cm in the case of TYPE-I launcher where microwave power was 1 kW and 1.5 kW at Ar gas pressure of 10 Pa.

incident power increases. When the input power was increased to 1.5 kW, the plasma discharge fully covered the whole area of the launcher. Spatial distributions of ion saturation currents were measured by scanning the Langmuir probe horizontally at an axial position of $z = 11$ cm away from the launcher surface, where the microwave powers were 1 kW and 1.5 kW at pressure of 10 Pa. It is shown in figure 4 that density profiles have a peak at the centre. Peak electron densities were estimated to be roughly 0.8×10^{11} cm^{-3} for 1 kW and 1.2×10^{11} cm^{-3} for 1.5 kW, respectively. Although we could not measure the density near the launcher surface, it is expected that the electron density is higher than the critical plasma density for the SWP, that is, 3.6×10^{11} cm^{-3}.

As shown in figure 4, plasma densities rapidly decreased with the radial position. As discussed later, observed density profiles are correlated closely with the spatial distribution of the electric field near the launcher surface.

Next, we tested the second type of microwave launcher, TYPE-II launcher, where the circular stainless steel punched plate with a diameter of 200 mm was attached to block the central part of the quartz plate, as shown in figure 2(*b*). The picture of the typical Ar plasma discharge is shown in figure 5. With the TYPE-II launcher, we observed more uniform density profiles with a uniformity of $\pm 3.5\%$ over a radius of 160 mm, as shown in figure 6, which were measured at $z = 11$ cm from the launcher where the microwave powers were 500 W

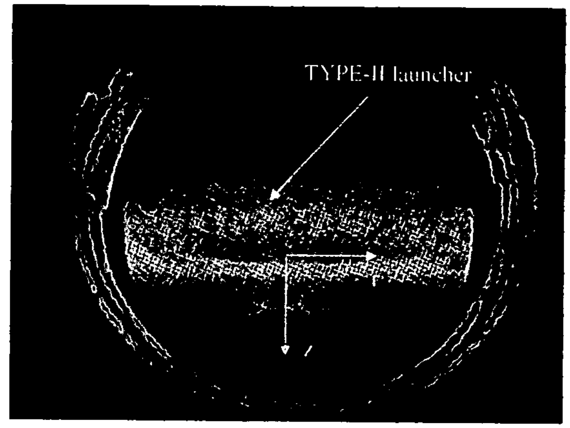

Figure 5. Pictures of Ar plasma discharges in case of TYPE-II launcher where microwave power was 500 W at a pressure of 17.3 Pa.

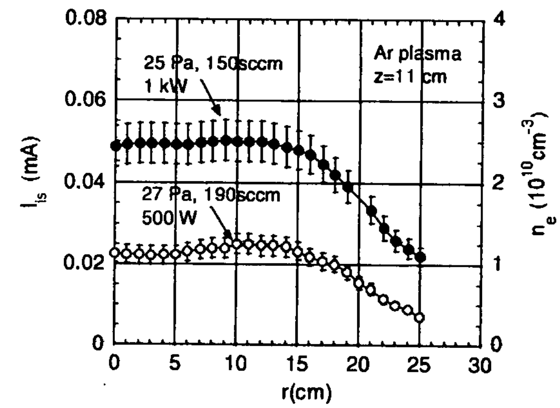

Figure 6. Spatial distributions of ion saturation currents at $z = 11$ cm in the case of TYPE-II launcher, where input powers were 1 kW at pressure of 25 Pa and 500 W at 27 Pa.

at 27 Pa and 1 kW at 25 Pa. Electron densities correspond to roughly 1×10^{10} cm^{-3} when the power was 500 W and $2 \sim 3 \times 10^{10}$ cm^{-3} when the power was 1 kW, which are low compared with the results in the TYPE-I launcher, since a strongly hollow type of profile near the launcher was gradually diffused and broadened in the downstream region. When changing the input power up to 1.2 kW at a pressure of 25 Pa, ion saturation currents measured at $r = 0$ and $z = 11$ cm smoothly increased without any density jumps, as shown in figure 7. At higher pressure up to 100 Pa, we also observed similar uniform density profiles and a linear relation between the incident power and electron density. Therefore, it is insisted that the SWP can be produced without density jumps in the case of the TYPE-II launcher.

4. Field analysis using the MAFIA simulator

To investigate the field distribution launched from the microwave launcher, we performed a numerical simulation using the MAFIA. In the present MAFIA simulator, Maxwell's equations in the Cartesian coordinates are calculated to figure out the field distributions inside and outside of the microwave launcher. Orthogonal electric field components, E_x, E_y,

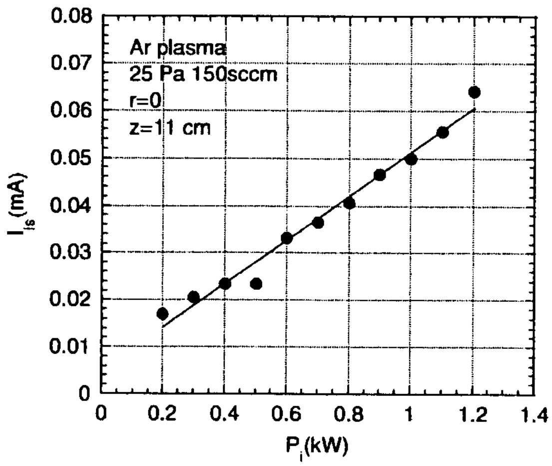

Figure 7. Relation between ion saturation currents and incident microwave power in the case of TYPE-II launcher.

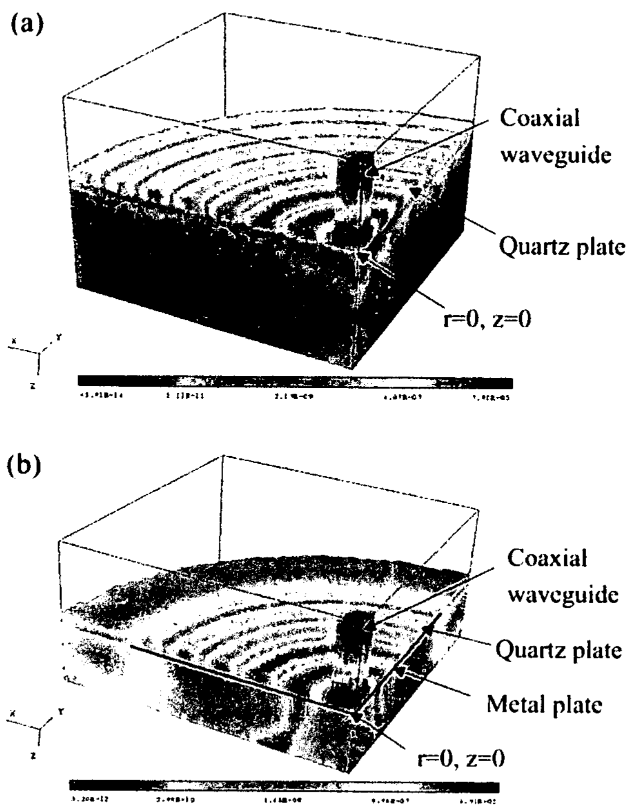

Figure 8. Calculation results of field intensity distributions of electric filed intensity in the cases of (*a*) TYPE-I and (*b*) TYPE-II launchers.

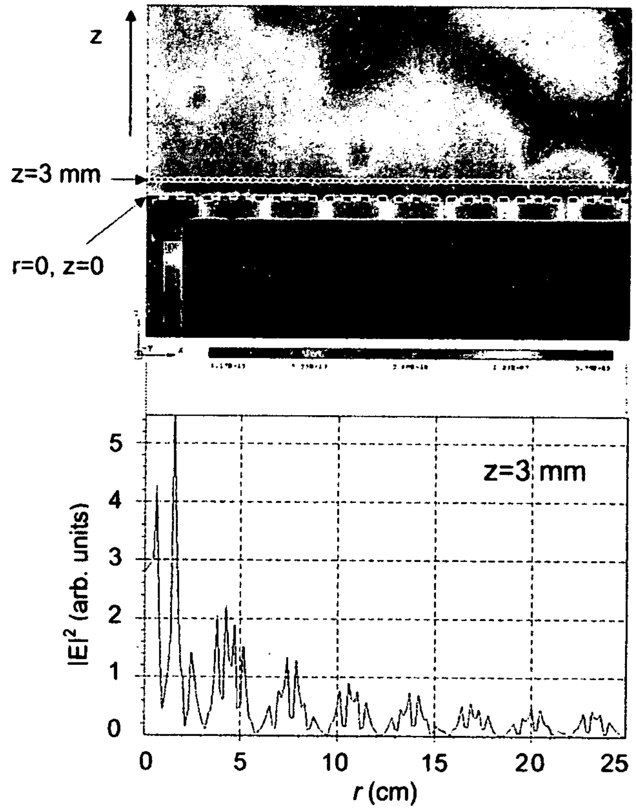

Figure 9. Calculation results of cross sectional plot and radial distribution of radiated microwave intensity in the case of TYPE-I.

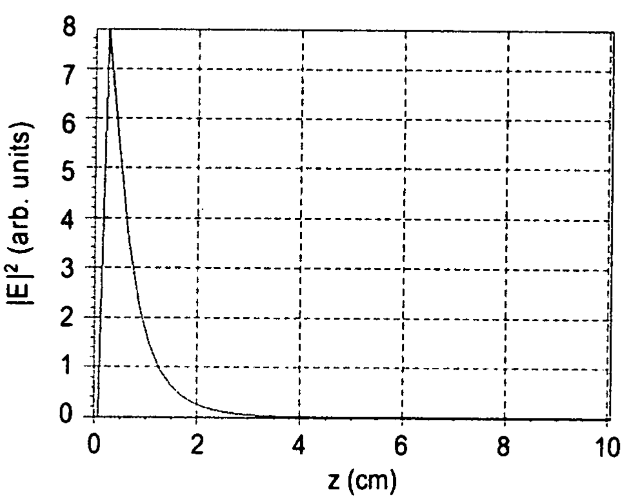

Figure 10. Calculation result of axial distribution of microwave intensity penetrating through small holes in the case of TYPE-I launcher, where the hole size was 6 mm in diameter and spacing of holes was 9 mm.

and E_z, are calculated in the MAFIA simulator, and spatial distributions of field intensity $|E|^2$ are plotted in figures 8–10. In the numerical calculation, we assumed that the rear side of the microwave launcher was simply a conductor and used the dielectric permittivity of 3.78 for the quartz plate.

Figures 8(*a*) and (*b*) show results of the field analysis of the spatial distributions of electric filed intensity in the cases of TYPE-I and TYPE-II launchers, respectively. Here, we set that a spacing between the launcher and substrate stage, *d*, is 100 mm in figure 8(*a*) and 50 mm in figure 8(*b*). Thus, the field distributions inside the chamber were different. Figure 8(*a*) shows one example of the spatial distribution of field intensity radiated from the TYPE-I launcher. In the case of TYPE-I, the microwave field fully spreads toward the edge of the quartz plate and forms a concentric resonant field pattern of transverse magnetic (TM) mode with an azimuthal mode number $m = 0$ and a radial mode number $n = 8$. It is seen that the field strength below the launcher is strong in the central region of the launcher. This is consistent with the plasma density distribution shown in figure 4, where the plasma density peaked

at the centre. On the other hand, figure 8(b) shows that the microwave propagates through the quartz plate radially and uniformly radiates toward the vacuum chamber from the bare quartz surface in the case of the TYPE-II launcher. It suggests that the plasma will be produced just below the bare quartz surface. Actually, the ring shaped plasma can be produced along the quartz surface, as shown in figure 5. Near the launcher surface, the plasma had a strongly hollow type distribution. However, due to the particle diffusion, the plasma became more uniform in the downward region, as shown in figure 6.

Lastly, it is noted that the wave field penetrating through a number of small holes is that of an evanescent wave. Figure 9 shows the cross sectional plot of the field intensity and radial distribution of electric field intensity at $z = 3$ mm in the case of the TYPE-I launcher. As seen in figure 9, the envelope of the electric field intensity distribution was of the zeroth Bessel function with azimuthal mode number $n = 0$ and radial mode number $n = 8$, that is, the TM_{08} mode. As shown before, these mode numbers were determined from the geometrical condition, such as cavity radius, wave frequency and dielectric constant of the material inside the cavity. From the resonant cavity theory (Jackson 1965), we can also show that the TM_{08} mode satisfies the resonant cavity condition.

Figure 10 shows one example of the axial distribution of the microwave intensity penetrating through small holes in the case of the TYPE-I launcher, where the hole size was 6 mm in diameter and spacing of holes was 9 mm. It is clearly seen that the field intensity rapidly decays through a number of small holes in the punched plate as an evanescent wave. From the simulation results in different hole sizes of 4–10 mm, it is also found that the decay lengths of the evanescent wave were typically 6–8 mm in the free space. Plasma can be produced by the evanescent waves penetrating through the small holes, when the wave field strength is strong enough to ionize the gas. In order to obtain a more uniform density profile in the case of the TYPE-I launcher, it will be necessary to design the optimum punched plate with spatially regulated hole distributions with different hole sizes and spacing.

5. Conclusion

In this study, we demonstrated novel types of planar cylindrical microwave launchers installed inside the vacuum chamber for production of large-area processing plasma. Two types of microwave launchers with closed and open cavity structures were tested to study the characteristics of plasma production. It is demonstrated that thin quartz plates of 10 mm thickness and 500 mm diameter in the case of the closed cavity structure and 15 mm thickness and 420 mm diameter in the case of the leaky open cavity one can be used for vacuum sealing in the internally mounted planar cylindrical launcher. Field analysis using the electromagnetic field simulator has been carried out to study the electric field distribution radiated from the launcher and to explain the experimental results. We showed that the production of uniform microwave plasma having a radius of roughly 160 mm was successfully demonstrated using the TYPE-II launcher at Ar gas pressure of $10 \sim 100$ Pa and an input power of 500–1200 W. Finally, we showed that the plasma density increased linearly with the incident microwave power without any density jumps.

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